JST-NSF-DFG-RCN Workshop on Distributed Energy Management Systems

April 20-22, 2015

Towards Harmonized Power System Control under Photovoltaic Power Prediction Uncertainty

Jun-ichi Imura

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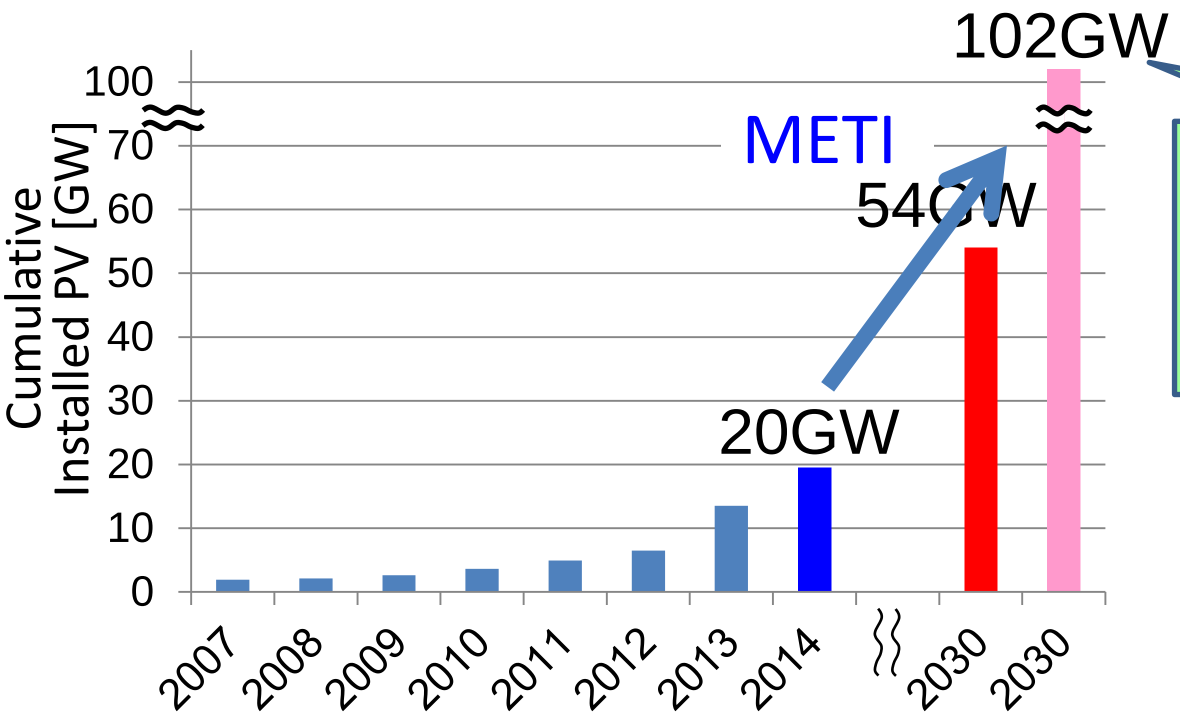
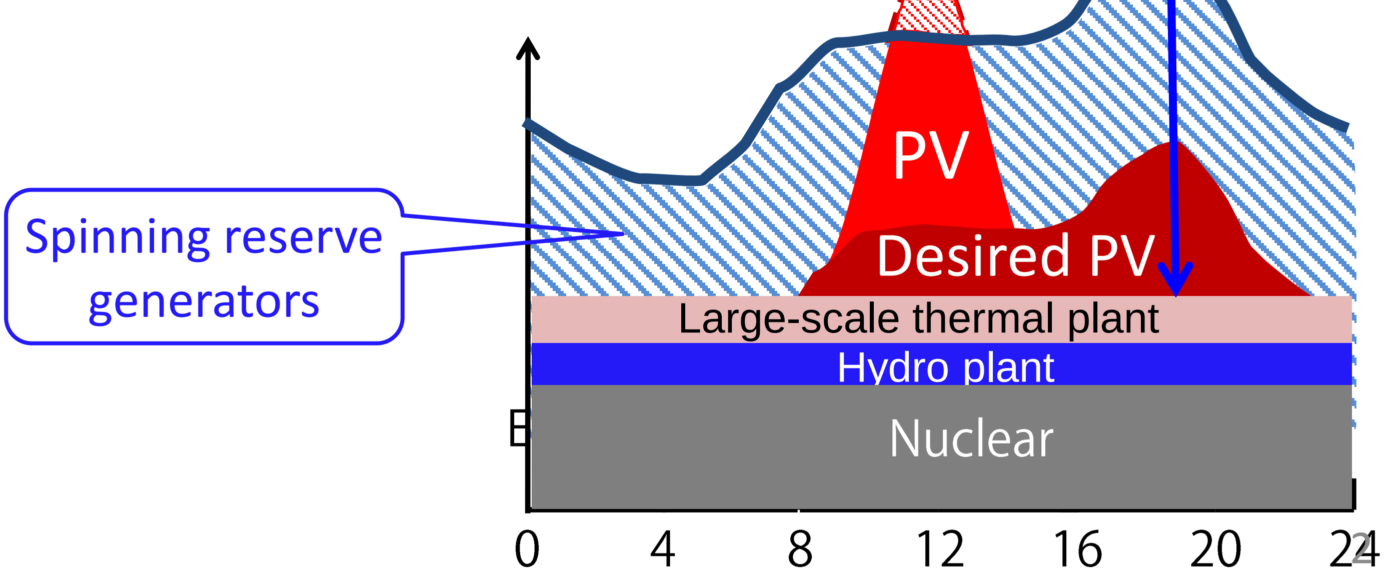
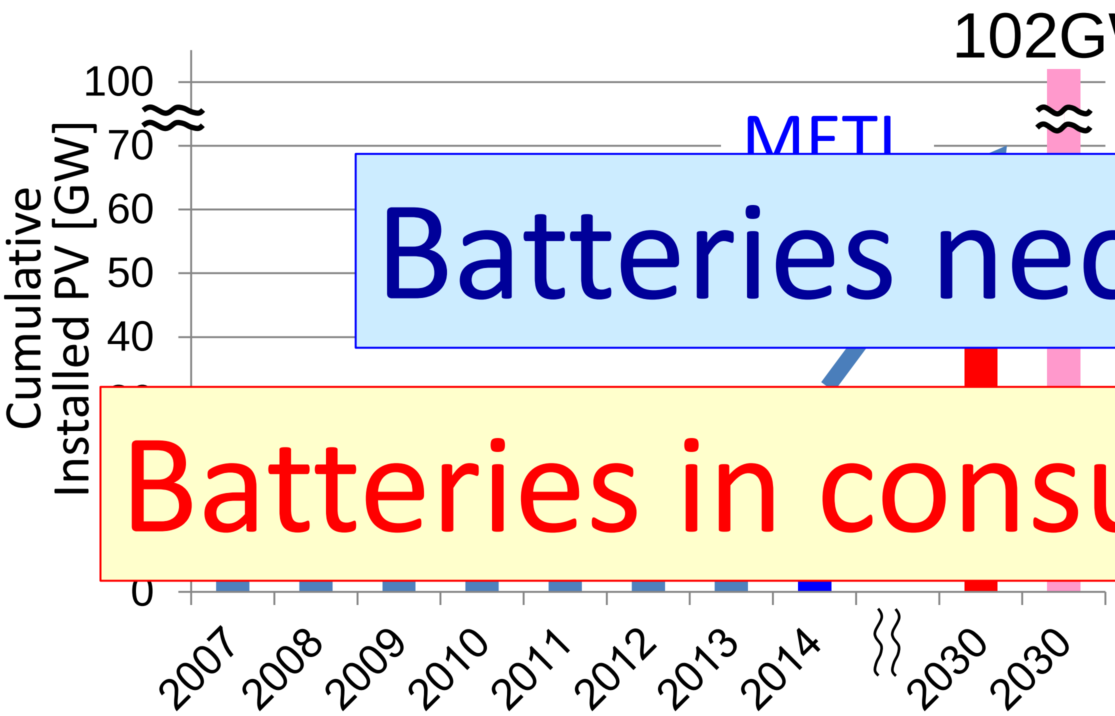
Installed PV Capacity in Japan



corresponds to 50% of power (10% of electric energy) consumption in Japan



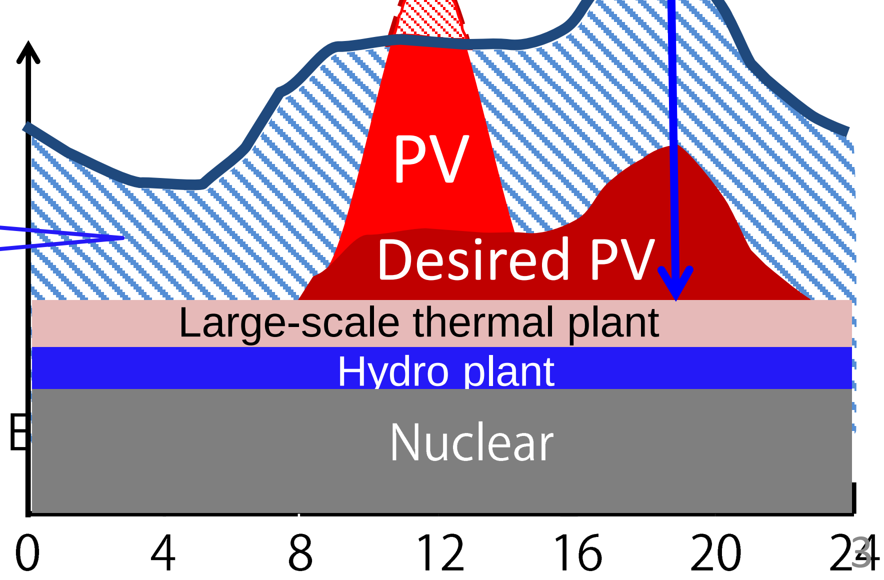
Installed PV Capacity in Japan



corresponds to 50% of … of electric … umption in Japan

Batteries necessary

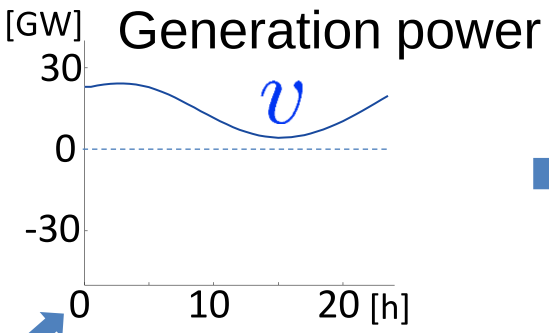
Batteries in consumer side!



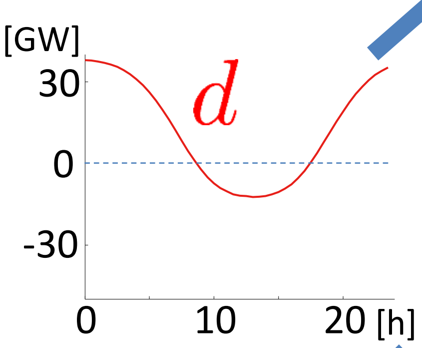
Spinning reserve generators

Framework of Supply-Demand-Storage Balancing

Supply side


Generation power

Day-ahead prediction of net load

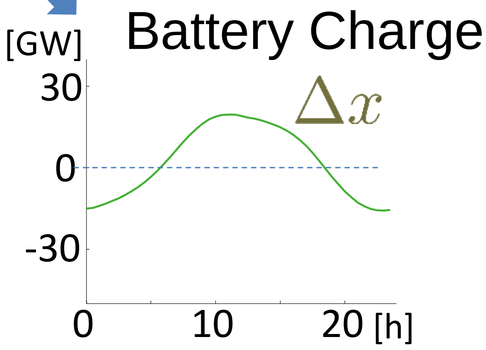


Day-ahead scheduling

Environmental and Economic Dispatch Control (EEDC)

$$d = v - \Delta x$$

“net load” is
load – PV


Battery Charge

Consumer side

Day-ahead scheduling

Unit commitment (UC)

Real-time operation

Economic Dispatch Control (EDC)

Day-ahead scheduling to aggregators

Harmonized Dispatch Plan (HDP)

- requests on battery C&D, power consumption, PV suppression along with incentive

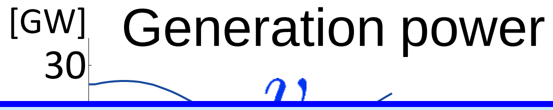
Real-time operation to consumers

Harmonized Consumer-side Control (HDC)

- Control based on the request by HDP and SOC of battery in each consumer

Framework of Supply-Demand-Storage Balancing

Supply side

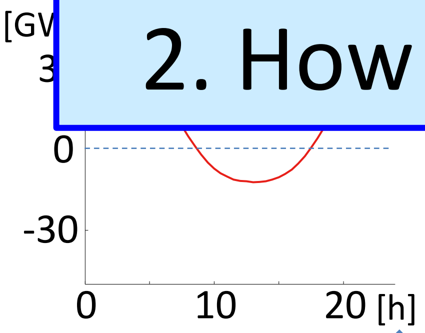


Day-ahead scheduling

Unit commitment (UC)

How we treat prediction uncertainty?

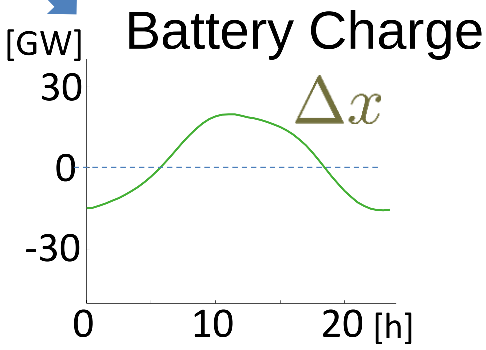
1. What prediction information effective?
2. How exploit this information?



Economic Dispatch Control (EEDC)

$$d = v - \Delta x$$

"net load" is load – PV



Consumer side

Harmonized Dispatch Plan (HDP)

- requests on battery C&D, power consumption, PV suppression along with incentive

Real-time operation to consumers

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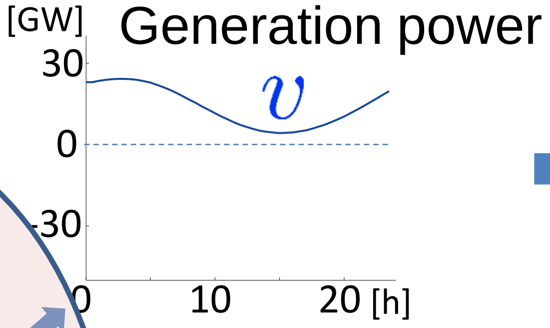
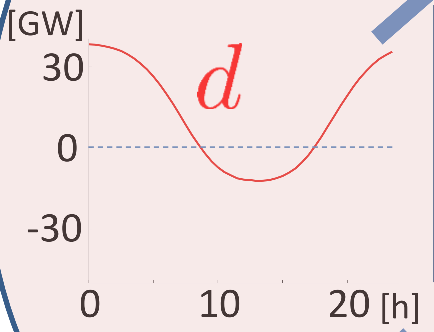
Framework of Supply-Demand-Storage Balancing

Supply side



Day-ahead prediction of net load



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Day-ahead scheduling

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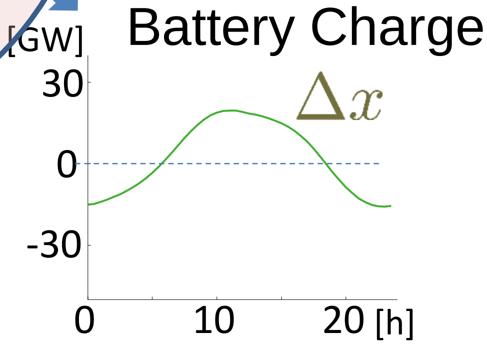

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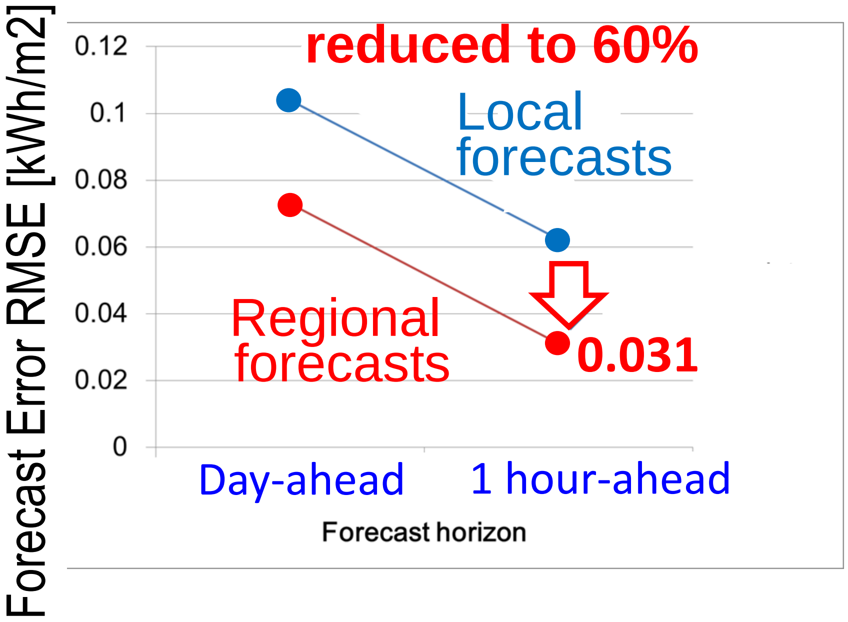
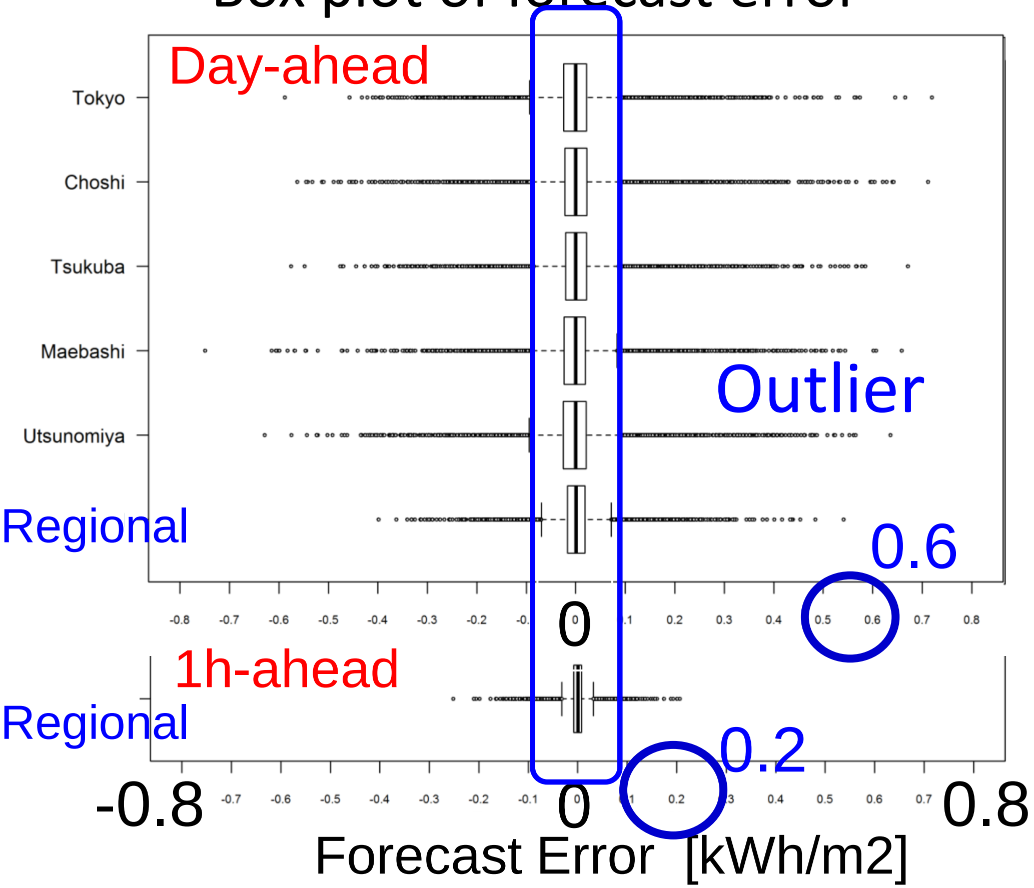
Forecast Error Evaluation

Numerical weather prediction based machine learning method
by Ozeki Group



0.031 [kWh/m2] implies error is 3GW for 100GW PV (3% error): very small !

Box plot of forecast error

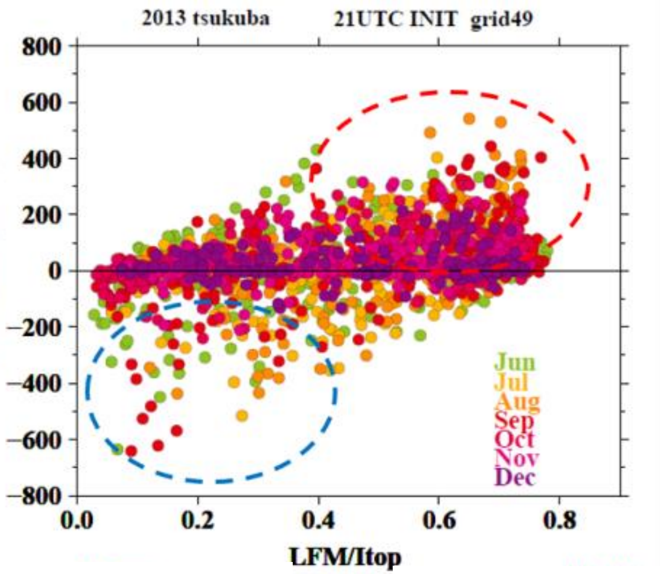


e.g., J.G.S. Fonseca Jr. et al., Progress in Photovoltaics Research and Applications 2014

Prediction Interval of PV Power Generation

Relation between Forecast error and Clearness Index

Forecast Error (kW/m2)

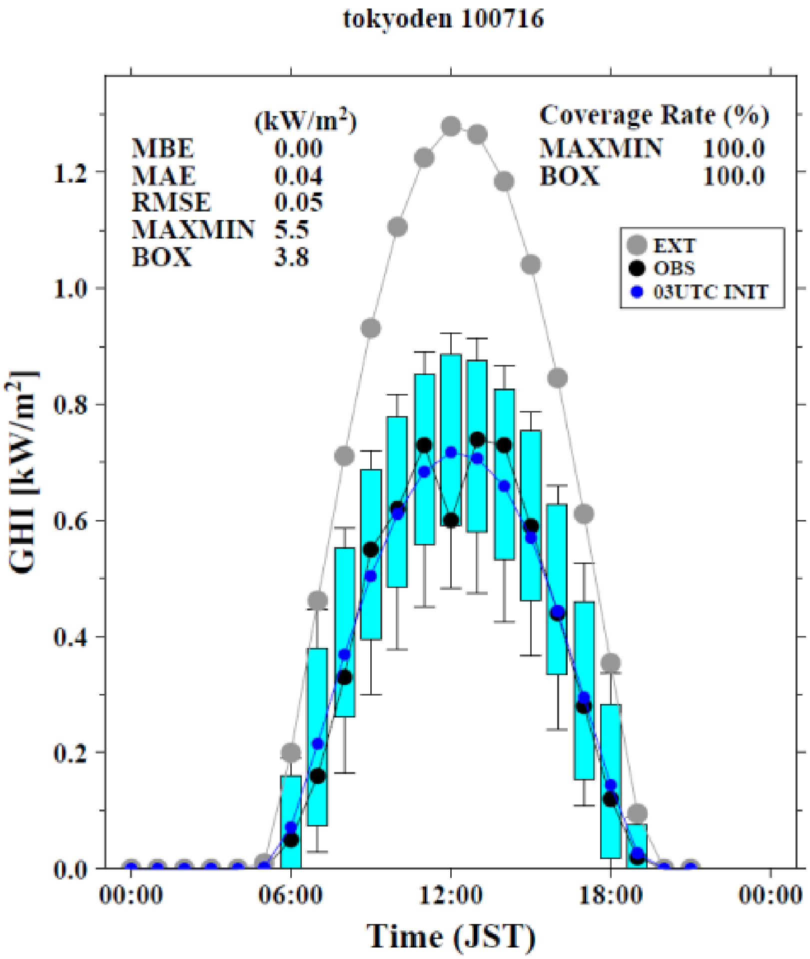


Overcast Day

Clear Sky Day

Forecasted Clearness Index

Prediction interval with confidence



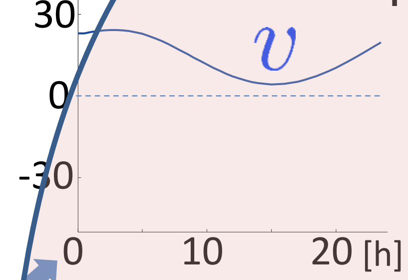
EXT: Extraterrestrial insolation

e.g., H. Ohtake et al., Energy Procedia, Vol. 59, pp.278-284, 2014

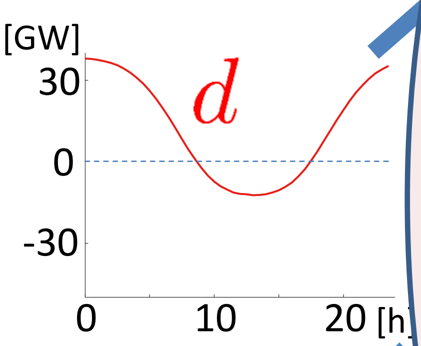
Framework of Supply-Demand-Storage Balancing

Supply side

Generation power



Day-ahead prediction of net load



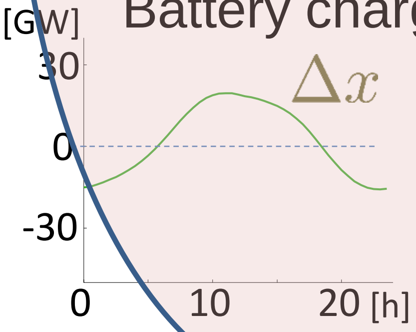
"net load" is
load – PV

Day-ahead scheduling

Environmental and Economic Dispatch Control (EEDC)

$$d = v - \Delta x$$

Battery charge



Consumer side

Day-ahead scheduling

Unit commitment (UC)

Real-time operation

Economic Dispatch Control (EDC)

Day-ahead scheduling to aggregators

Harmonized Dispatch Plan (HDP)

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Real-time operation to consumers

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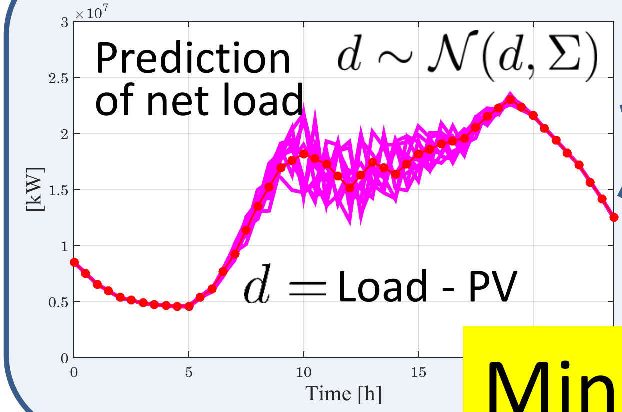
Stochastic Approach & Interval Approach

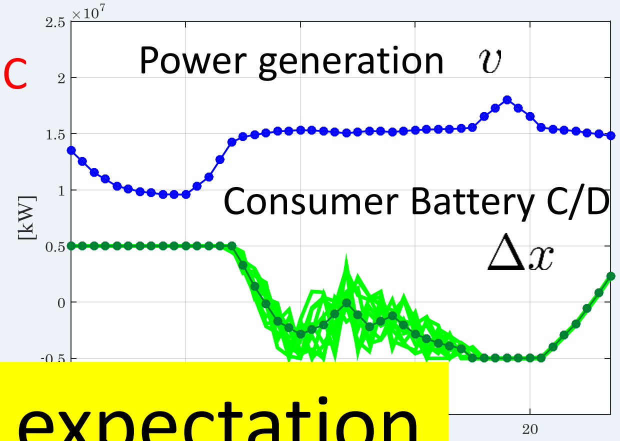
Stochastic Approach

Day ahead Scheduling

Operation



EEDC



UC

HDP

EDC

Operation based on short term forecast

HDC

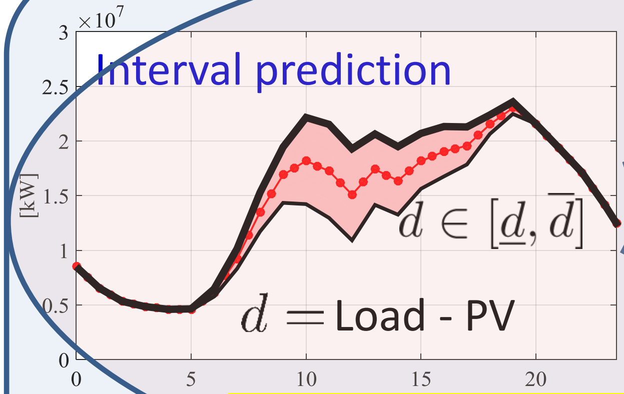
Aggregator based control

Min of expectation

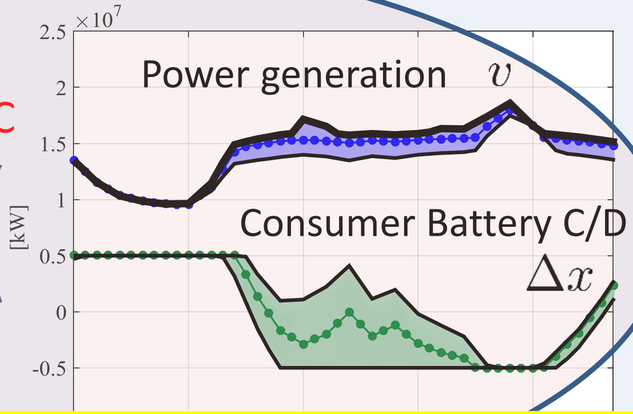
Interval Approach

Day ahead Scheduling

Operation



EEDC



UC

HDP

EDC

Operation based on short term forecast

HDC

Aggregator based control

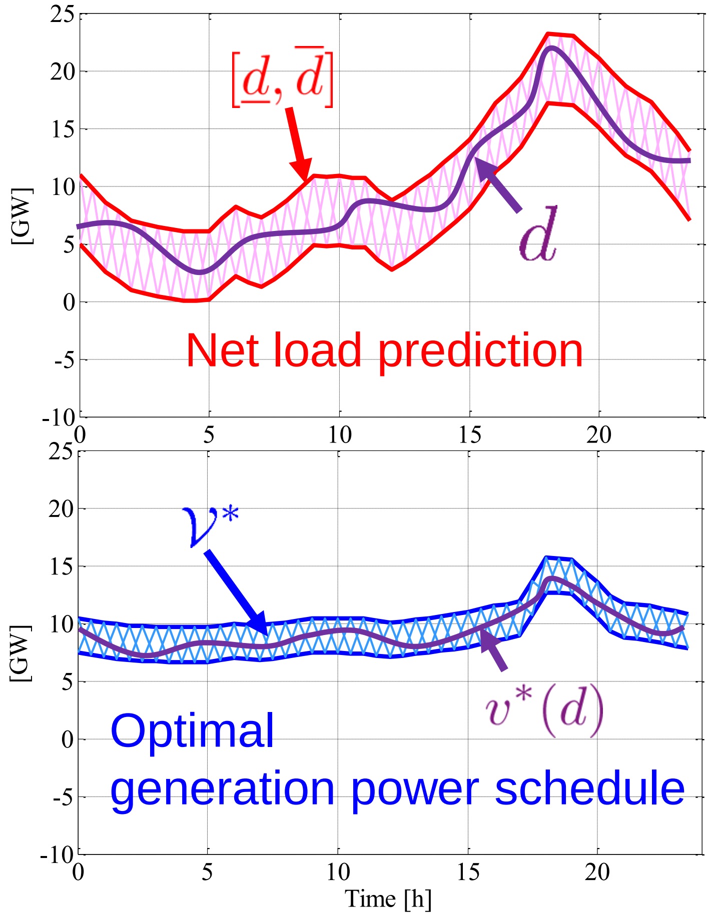
Can estimate regulating power reserves

Problem Formulation

[Problem]

Given an interval $[\underline{d}, \overline{d}] \subseteq \mathbb{R}^T$. Find $\mathcal{V}^* := \{v^*(d) | d \in [\underline{d}, \overline{d}]\}$

$$d := \begin{bmatrix} d(1) \\ d(2) \\ \vdots \\ d(T) \end{bmatrix}$$



Optimization problem

$$v^*(d) = \arg\min_{v} J(v)$$

Cost function

$$J(v) = \sum_{k=1}^{T} \{f(v(k)) + g(\Delta x^{\mathrm{out}}(k))\}$$

Fuel cost Battery deterioration cost

s.t.

$$x(k+1) = x(k) + \alpha \Delta x^{\mathrm{in}} - \frac{1}{\beta} \Delta x^{\mathrm{out}}$$

Battery stored energy

$$d(k) = v(k) - (\Delta x^{\mathrm{in}}(k) - \Delta x^{\mathrm{out}}(k))$$

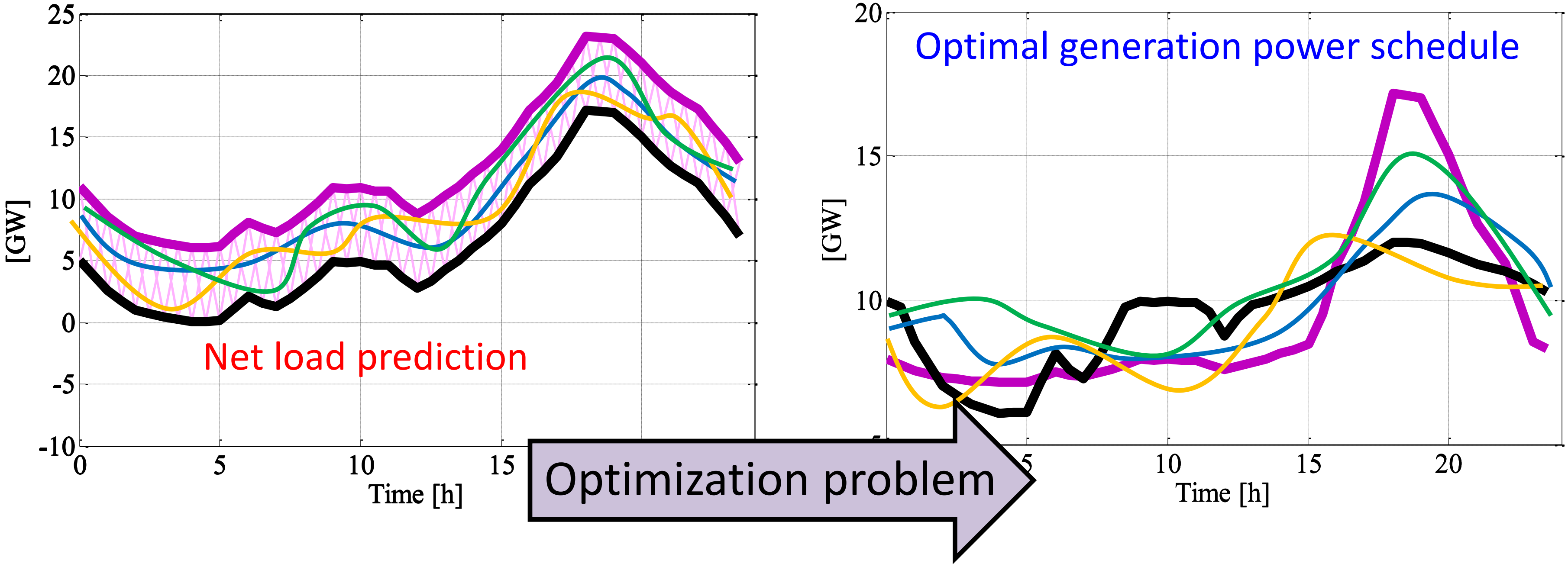
Net load

$$\Delta x^a_{\min} \leq \Delta x^a(k) \leq \Delta x^a_{\max} \quad a \in \{\mathrm{in}, \mathrm{out}\}$$

$$x_{\min} \leq x(k) \leq x_{\max}$$

$x(0) = x(T)$ To use battery sustainably

Interval Approach to Worst Case Scenario



Infinite number of trials may be required !

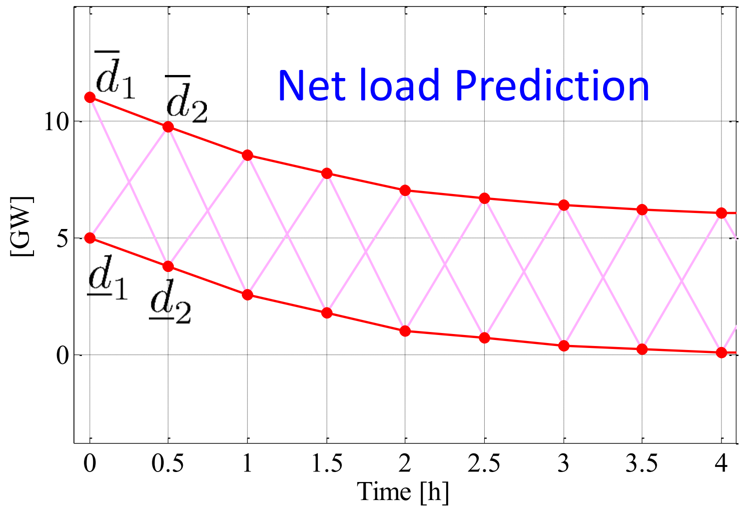
Hard to obtain the bounds of possible solutions for all net load predictions!

Monotonicity Based Approach

For example ···

$$\frac{\partial v^*(d)}{\partial d} := \begin{array}{c} \begin{array}{cccc} \text{Positive} & \text{Negative} & & \cdots \end{array} \\ \begin{bmatrix} \frac{\partial v_1^*}{\partial d_1} & \frac{\partial v_1^*}{\partial d_2} & \cdots & \frac{\partial v_1^*}{\partial d_{48}} \\ \frac{\partial v_2^*}{\partial d_1} & \frac{\partial v_2^*}{\partial d_2} & \cdots & \frac{\partial v_2^*}{\partial d_{48}} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{\partial v_{48}^*}{\partial d_1} & \frac{\partial v_{48}^*}{\partial d_2} & \cdots & \frac{\partial v_{48}^*}{\partial d_{48}} \end{bmatrix} \end{array}$$

$$d = \begin{bmatrix} d_1 & d_2 & \cdots & d_{48} \end{bmatrix}^T$$



(Sampling time: 0.5h)

$$v_1^*(\underline{d}_1, \overline{d}_2, \ldots, \overline{d}_{48}) \le v_1^*(d) \le v_1^*(\overline{d}_1, \underline{d}_2, \ldots, \underline{d}_{48})$$

$$v_2^*(\underline{d}_1, \underline{d}_2, \ldots, \overline{d}_{48}) \le v_2^*(d) \le v_2^*(\overline{d}_1, \overline{d}_2, \ldots, \underline{d}_{48})$$

$$\vdots$$

48×2 number of trials

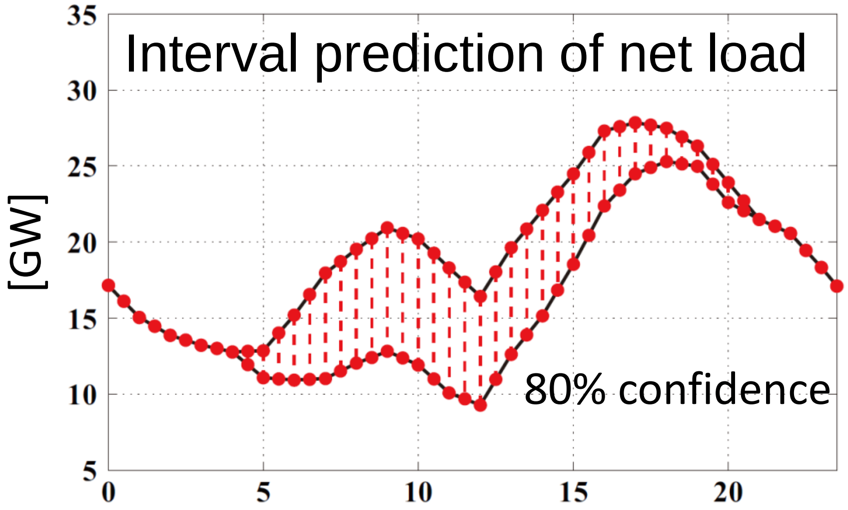
- can find the bounds of possible optimal solutions by finite trials
- can prove that the optimization problem is monotone w. r. t d

(the sign is constant)

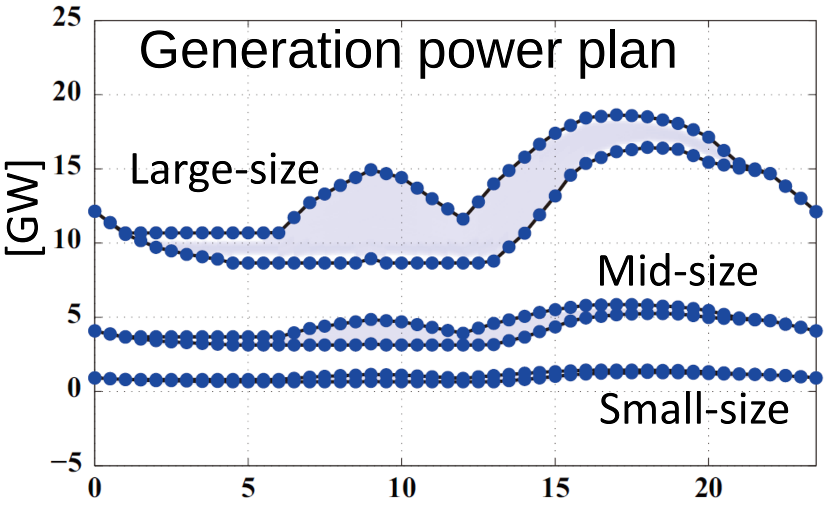
e.g., T. Ishizaki et al., Proc. of MTNS14, pp.792-799, 2014

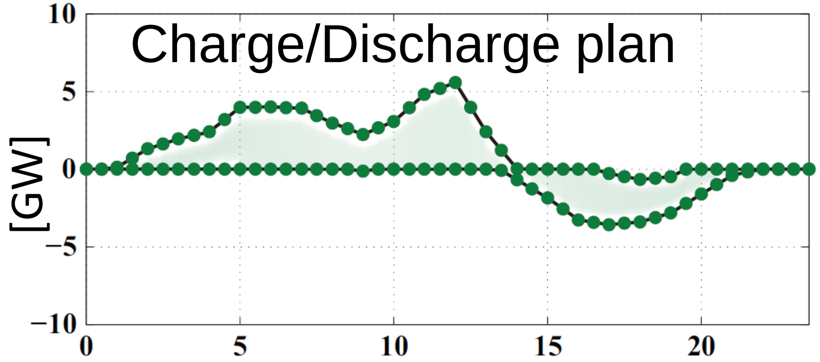
Simulation

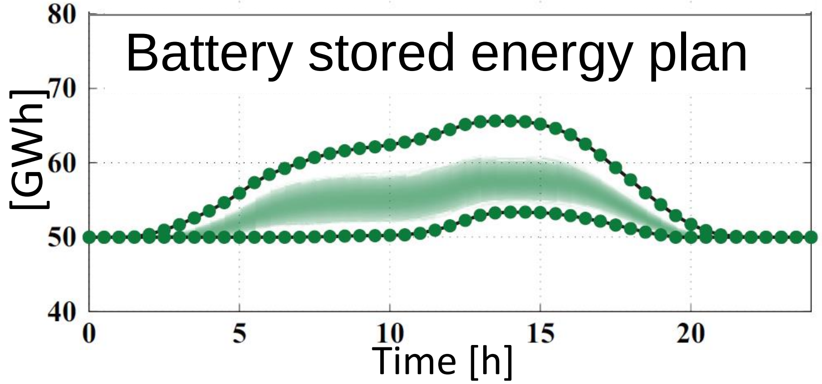
Area to be controlled	Tokyo (19million)
Load (max)	48[GW]
Installed PV (max)	23[GW] (26%)
Inverter capacity of installed Battery	±10[GW] (15%)
Installed Battery (max)	80[GWh] (15%)
C/D efficiency	0.9 for both


Interval prediction of net load

80% confidence


Generation power plan


Charge/Discharge plan

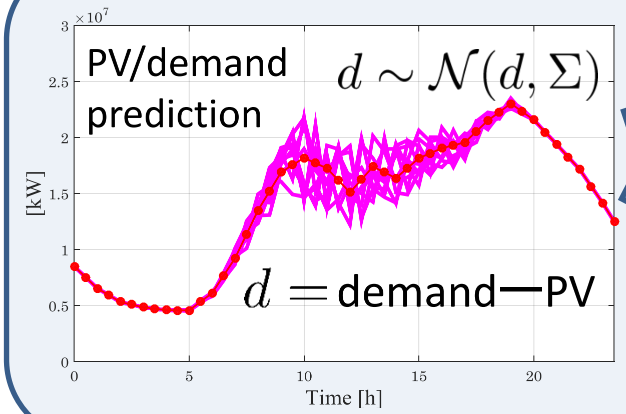

Battery stored energy plan

Stochastic Approach vs Interval Approach

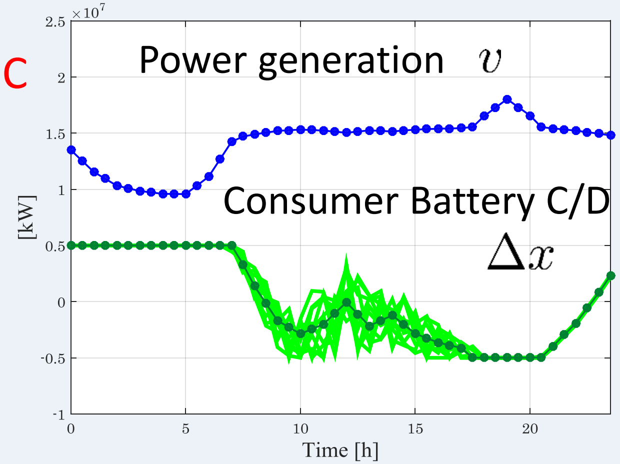
Stochastic Approach

Day ahead Scheduling

Operation



EEDC



UC

EDC
Operation based on short term forecast

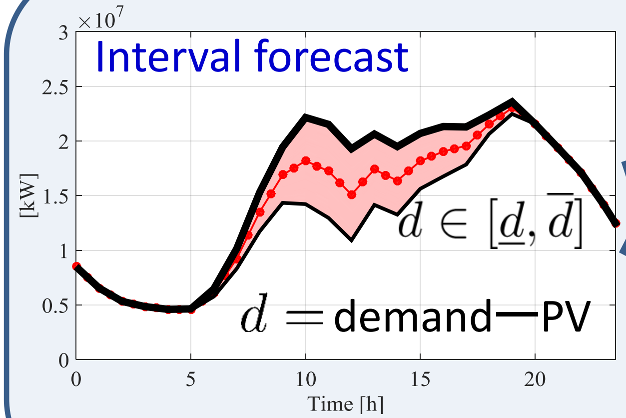
HDP

HDC
Aggregator based control

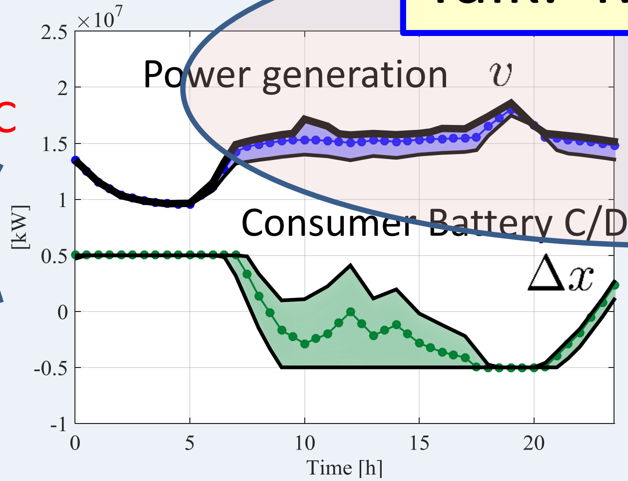
Interval Approach

Day ahead Scheduling

Operation



EEDC



Talk: Masuta Group

UC

EDC
Operation based on short term forecast

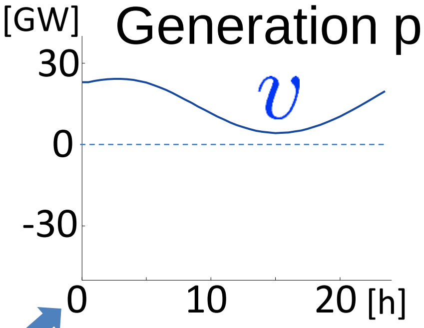
HDP

HDC
Aggregator based control

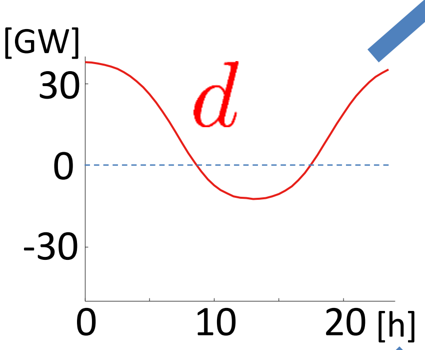
Framework of Supply-Demand-Storage Balancing

Supply side

Generation power



Day-ahead prediction of net load



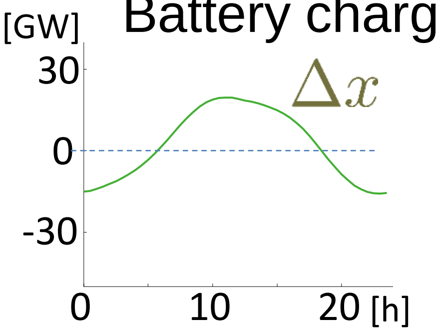
Day-ahead scheduling

Environmental and Economic Dispatch Control (EEDC)

$$d = v - \Delta x$$

“net load” is
load – PV

Battery charge



Consumer side

Day-ahead scheduling

Unit commitment (UC)

Real-time operation

Economic Dispatch Control (EDC)

Day-ahead scheduling to aggregators

Harmonized Dispatch Plan (HDP)

- requests on battery C&D, power consumption, PV suppression along with incentive

Real-time operation to consumers

Harmonized Consumer-side Control (HDC)

-Control based on the request by HDP and SOC of battery in each consumer

HDP (Harmonized Dispatch Plan)

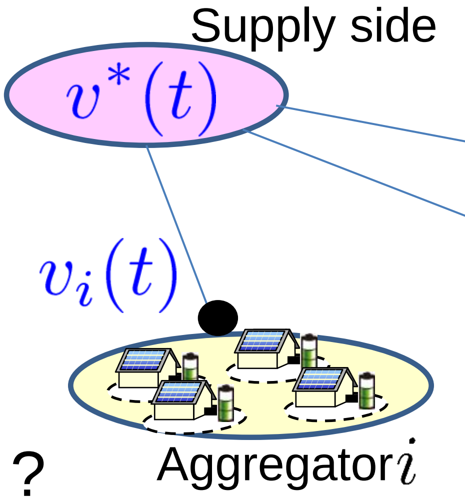
Entire system: $d(t) = v(t) - \Delta x(t)$

Aggregator i: $d_i(t) = v_i(t) - \Delta x_i(t)$, $\quad i = 1, \ldots, N$

Day-ahead prediction of net load

Charge power of battery

Power at NW connection point (consumption power)



Problem of finding requests to Aggregators

Given $v^*(t)$ and $d_i(t)$, $i = 1, \ldots, N$,

find $v_i(t)$, $i = 1, \ldots, N$ such that $\sum_{i=1}^{N} v_i(t) \simeq v^*(t)$

s.t. constraints on battery capacity etc.

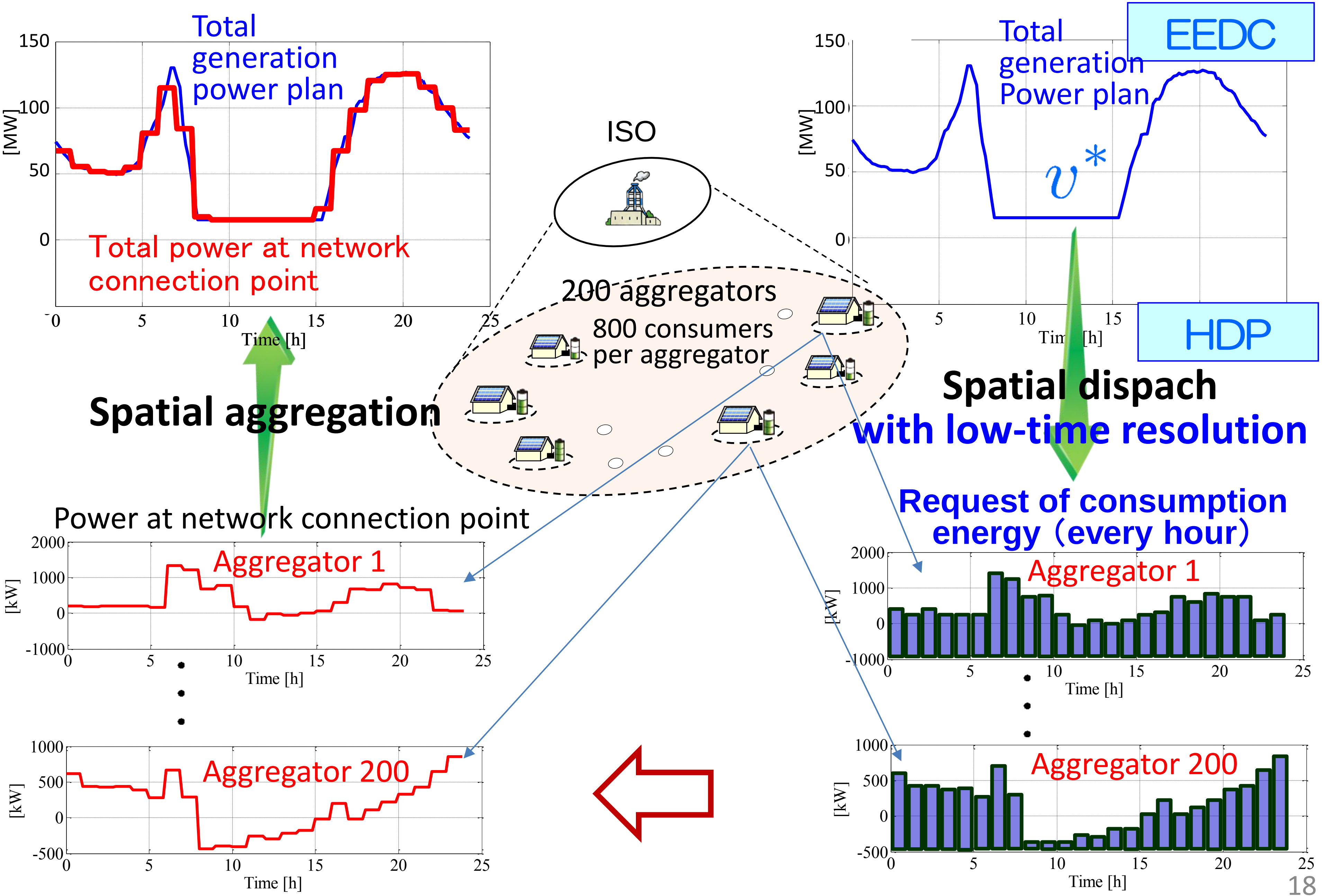
How should we deal with prediction uncertainty ?

Consider **low-time-resolved requests !**

- Prediction uncertainty is reduced
- Constraints are relaxed
- Flexibility of consumers is increased

e.g., T. Sadamoto, et al., IEEE Trans on Smart Grid, 6-2, 853-865, 2015

HDP: Low-time Resolution Request

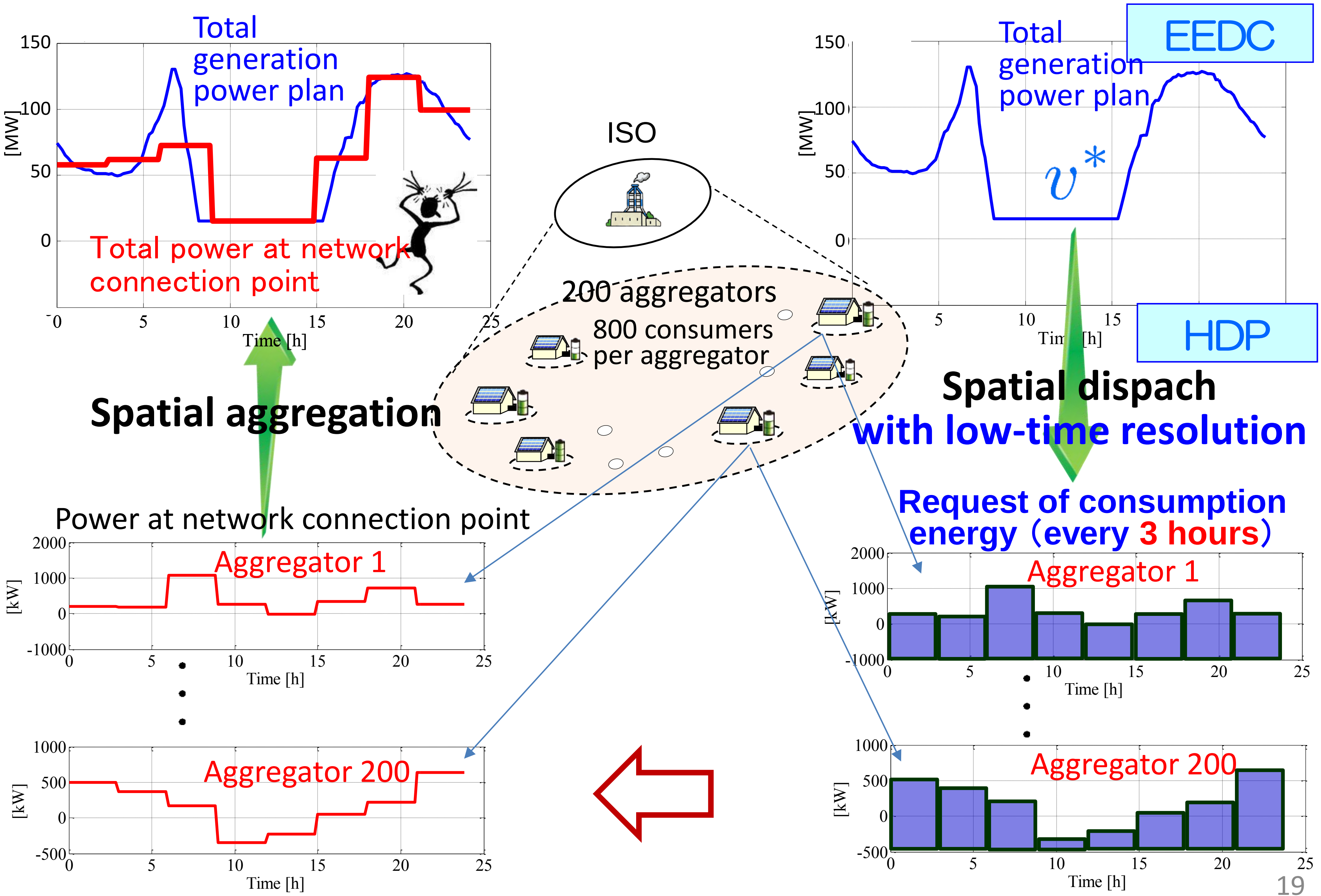


Spatial aggregation

Spatial dispach with low-time resolution

Request of consumption energy（every hour)

HDP: Low-time Resolution Request



Total generation power plan

Total power at network connection point

Spatial aggregation

Power at network connection point

ISO

200 aggregators

800 consumers per aggregator

EEDC

Total generation power plan

v^*

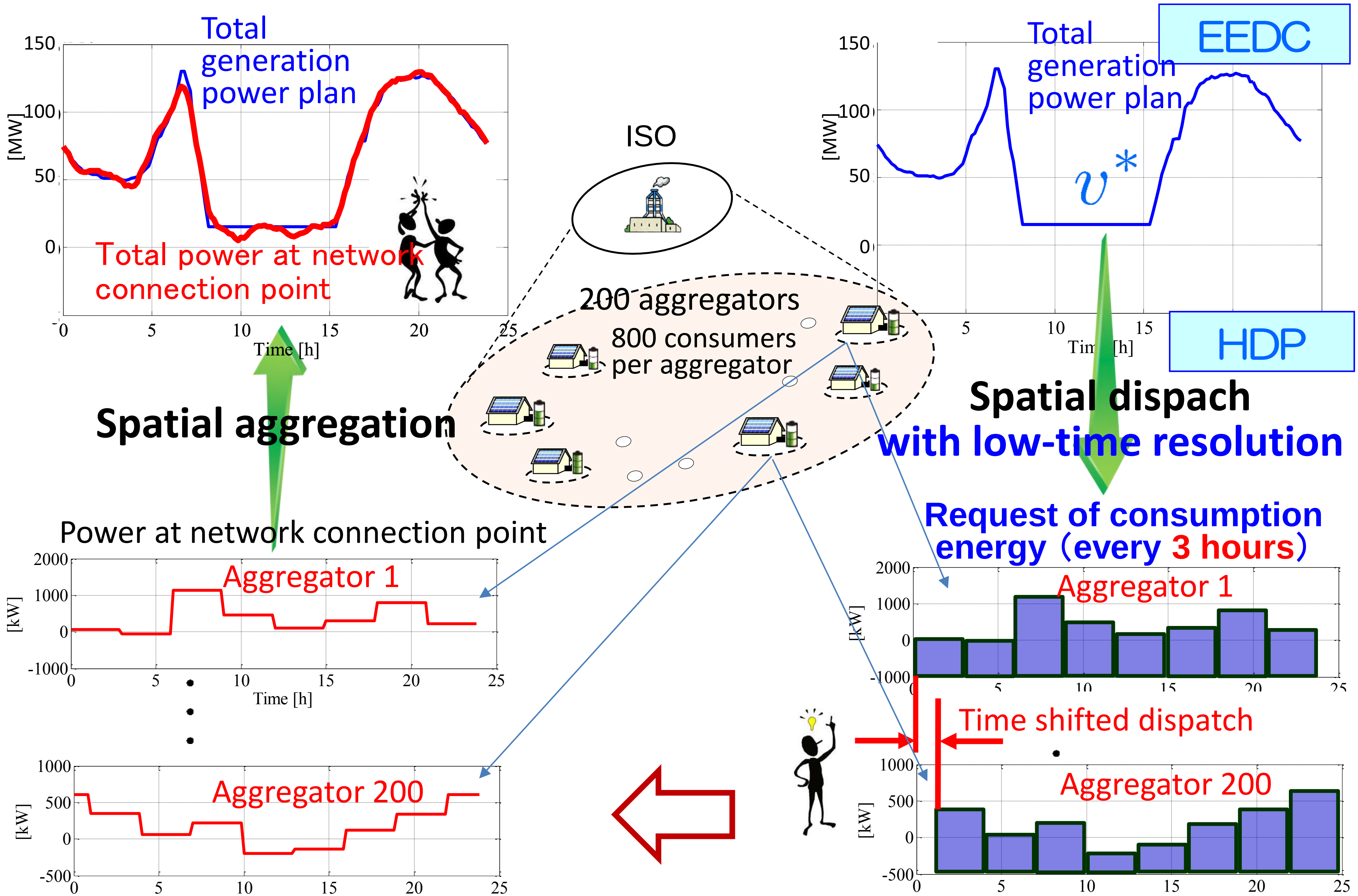
HDP

Spatial dispach

with low-time resolution

Request of consumption energy（every 3 hours）

HDP: Time Shifted Request



Total generation power plan

Total power at network connection point

Spatial aggregation

ISO

200 aggregators

800 consumers per aggregator

EEDC

Total generation power plan

v^*

HDP

Spatial dispach

with low-time resolution

Power at network connection point

Aggregator 1

Aggregator 200

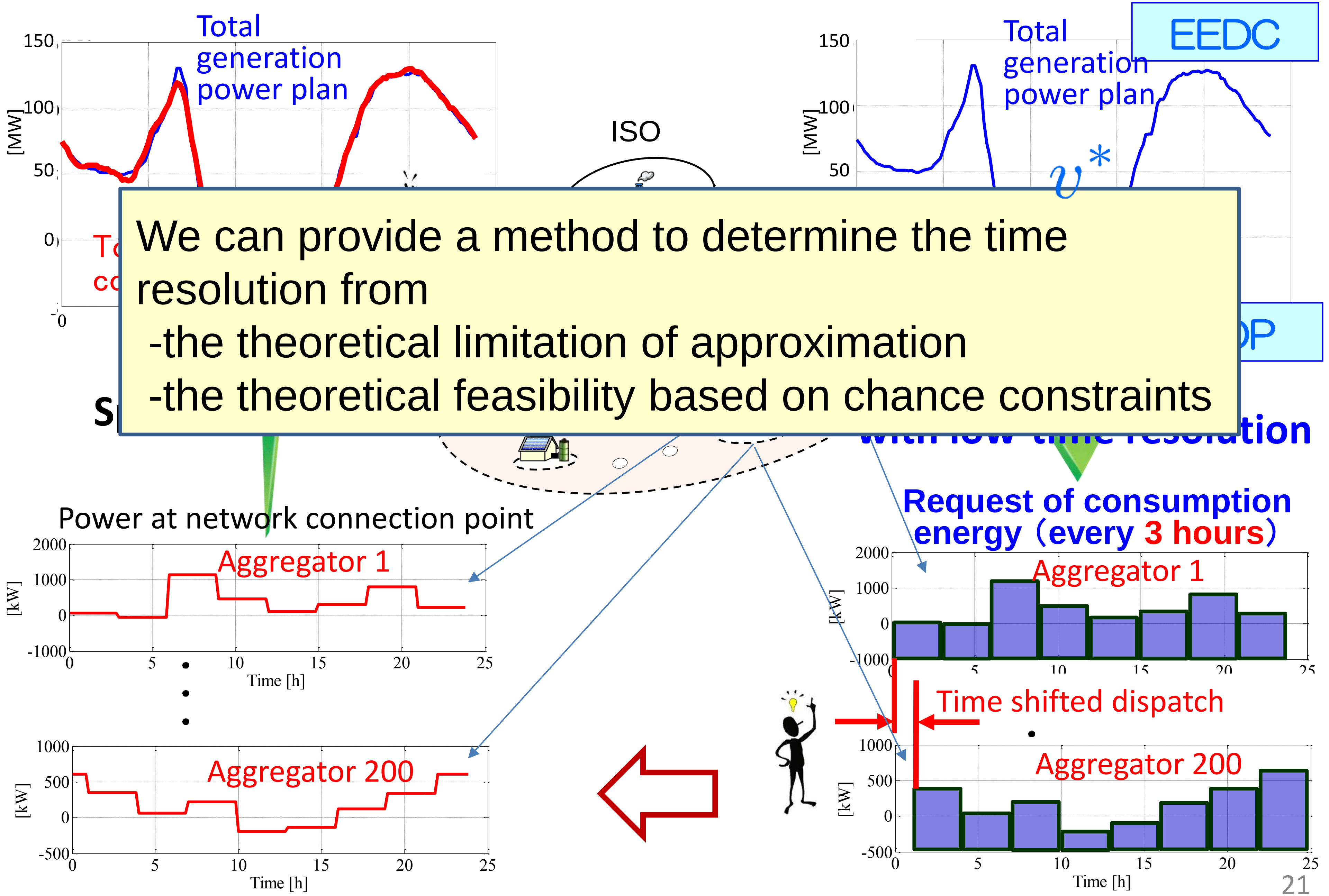
Request of consumption energy（every 3 hours）

Aggregator 1

Time shifted dispatch

Aggregator 200

HDP: Time Shifted Request



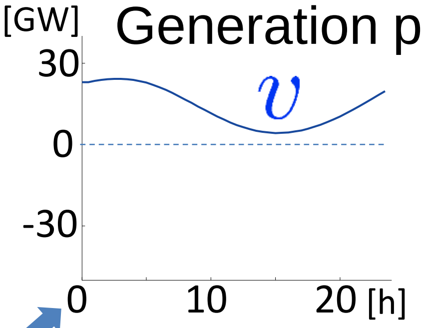
We can provide a method to determine the time resolution from

-the theoretical limitation of approximation

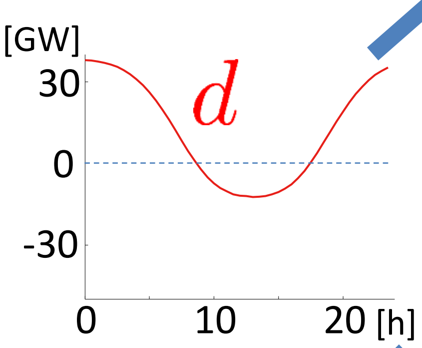
-the theoretical feasibility based on chance constraints

Framework of Supply-Demand-Storage Balancing

Supply side



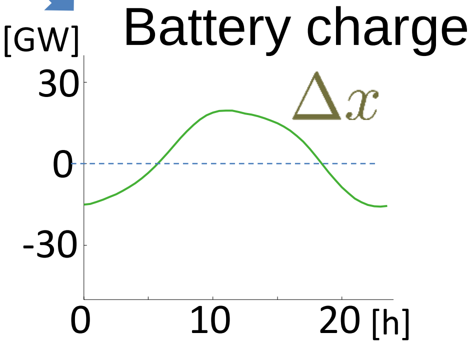
Day-ahead prediction of net load



"net load" is
load – PV

Day-ahead scheduling
Environmental and Economic Dispatch Control (EEDC)

$$d = v - \Delta x$$



Consumer side

Day-ahead scheduling
Unit commitment (UC)

Real-time operation
Economic Dispatch Control (EDC)

Day-ahead scheduling to aggregators
Harmonized Dispatch Plan (HDP)
- requests on battery C&D, power consumption, PV suppression along with incentive

Poster: Ueda group

Real-time operation to consumers
Harmonized Consumer-side Control (HDC)
- Control based on the request by HDP and SOC of battery in each consumer

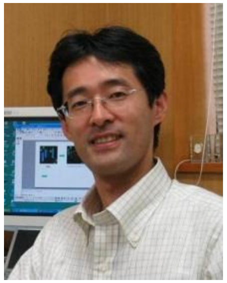
JST CREST Past Project Team

Project title: Optimal Dispatch Control of Huge-Scale Power Systems under Prediction Uncertainty of Photovoltaic Power Generation

Term: October 2013 – March 2015 (2.5 years)

PI: Jun-ichi Imura (Tokyo Institute of Technology)

4 Group leaders (17 researchers)



Jun-ichi Imura
(Tokyo Tech)

Yuzuru Ueda
(Tokyo U of Science)

Taisuke Masuta
(The Institute of Applied Energy)

Taisuke Masuta
(Advanced Industrial Science and Technology)

Systems and Control

Power Systems Engineering

Meteorological Engineering

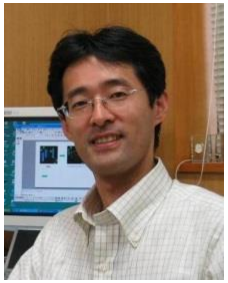
JST CREST Renewed Project Team

Project title: System Theory for Harmonized Power System Control
Based on Photovoltaic Power Prediction

Term: April 2015 – March 2020 (5 years)

PI: Jun-ichi Imura (Tokyo Institute of Technology)

12 Group leaders (59 researchers in total):


Jun-ichi Imura
(Tokyo Tech)


Shinji Hara
(U of Tokyo)


Yoshito Ohta
(Kyoto U)


Yuzuru Ueda
(Tokyo U of Science)


Hideharu Sugihara
(Osaka U)

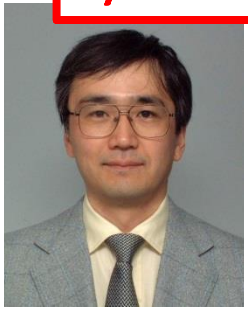

Taisuke Masuta
(IAE)

Systems and Control

Math. Science

Meteorological Engineering

Power systems


Akira Kojima
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Shun-ichi Azuma
(Kyoto U)


Hideyuki Suzuki
(U of Tokyo)


Akinobu Murata
(AIST)


Yoshifumi Zouka
(Hiroshima U)


Nobuyuki Yamaguchi
(Tokyo U of Science)

Project Research Topics

Target: System Theory for Harmonized Power System Control Based on Photovoltaic Power Prediction

PV-prediction based, Spatiotemporally Cooperative Power System Control

- To deal with prediction uncertainty with heavy-tail distribution, need stronger ST-cooperation of various controls such as EEDC,UC,EDC,LFC,GF,DR,HDP,HDC,…. including control of transmission/distribution networks

- Collaboration room with digital power system simulator

Structure Design of Power System including Mid-layer

- Roles of mid-layer including aggregators
- Markets points of view